Merging matrix elements & parton showers

Frank Krauss

IPPP Durham

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or: How to embed matrix elements
without destroying the accuracy of the shower

(independent of the shower)

This talk is primarily based on
S.Hoeche, F.K., S.Schumann, & F.Siegert, JHEP 0905 (2009) 053

see also: K.Hamilton, P.Richardson, J.Tully, arXiv:0905.3072 [hep-ph]
for an implementation with angular ordered showers

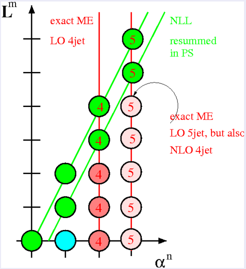
Matrix elements vs. parton showers

- Different perturbative expansions: fixed order vs. log order.
- Different realms of applicability.

ME vs. PS

- MEs: hard, large-angle emissions; all interferences.
- PS: soft, collinear emissions; resummation of large logarithms, not all interferences.
- Combine both, avoid double-counting. (positive and negative)

α_s vs. Log



Reminder: The parton shower

- Remember Sudakov form factor (no emission probability):

$$\Delta_a(t,\, t_0) = \exp\left\{-\int\limits_{t_0}^{t}\frac{\mathrm{d}t'}{t'}\int\limits_{\zeta_{\min}}^{\zeta_{\max}}\mathrm{d}\zeta\sum_{b=q,g}\mathcal{K}_{ab}(\zeta,t')\right\}.$$

- Here: $\mathcal{K}_{ba}(\zeta,t)$ = splitting kernels of evolution

($\Longrightarrow$ Altarelli-Parisi splitting functions for DGLAP evolution)

Also: $\zeta_{\max}$ = resolution criterion, $t,\, t'$ = evolution parameters.

- Starting from a scale T, find next emission off parton a at t through

$$\#_{\rm random} = \mathcal{P}_a(T,\, t) \equiv \frac{\Delta_a(T,\, t_0)}{\Delta_a(t,\, t_0)}\,,$$

with $t_0 = \mathcal{O}(\mathrm{few}\,\Lambda^2_{\rm QCD})$ as infrared cut-off.

($\Longrightarrow$ add ratio of PDFs for initial state shower: backward evolution trick)

Strategy for merging

S.Catani, F.K., R.Kuhn and B.R.Webber, JHEP **0111** (2001) 063
F.K., JHEP **0208** (2002) 015

- Basic idea: Decompose phase space into hard, wide-angle and soft, collinear region through jet measure. Use MEs in hard region (jet production), PS in soft region (jet evolution).
- Realise that parton shower approximation to matrix element is at LO is product of splitting functions.
- (Leading) Logarithmic HO corrections are included through Sudakov form factors and running of α_S.
- Therefore: replace product of splitting functions with ME, keep HO effects of shower.
- In original papers above: Reweight ME with appropriate Sudakov form factors and ratios of α_S, run a vetoed shower. In e^+e^- for angular-ordered shower: NLL accuracy achievable.
- Question(s): Accuracy in IS shower, relationship to other merging procedures (e.g. CKKW-L, MLM)

A new attempt to formalise merging

- Goal: Make preservation of log accuracy in shower explicit.
- First replace kernels in QCD evolution equations with

$$\mathcal{K}_{ab}(\xi,\bar{t}) \;=\; \mathcal{K}^{\rm ME}_{ab}(\xi,\bar{t})+\mathcal{K}^{\rm PS}_{ab}(\xi,\bar{t})\,.$$

with (Q is jet measure of jet clustering algorithm)

$$\begin{aligned}\mathcal{K}^{\rm ME}_{ab}(\xi,\bar{t}) &= \mathcal{K}_{ab}(\xi,\bar{t})\Theta\left[Q_{ab}(\xi,\bar{t})-Q_{\rm cut}\right] \qquad \text{and}\\ \mathcal{K}^{\rm PS}_{ab}(\xi,\bar{t}) &= \mathcal{K}_{ab}(\xi,\bar{t})\Theta\left[Q_{\rm cut}-Q_{ab}(\xi,\bar{t})\right]\,.\end{aligned}$$

- Yields modified Sudakov form factor (decomposes trivially):

$$\Delta_a(t,\,t_0)=\Delta^{\rm ME}_a(t,\,t_0)\cdot\Delta^{\rm PS}_a(t,\,t_0)\,.$$

and no-emission probabilities (interpretation see below)

$$\mathcal{P}_a(T,\,t)=\mathcal{P}^{\rm ME}_a(T,\,t)\cdot\mathcal{P}^{\rm PS}_a(T,\,t)\,.$$

The PS regime: Truncated showers

- Look into PS-splitting kernel:

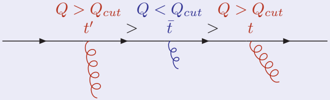
$$\mathcal{K}_{ab}^{\rm PS}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\Theta\left[Q_{\rm cut} - Q_{ab}(\xi,\bar{t})\right]\,.$$

$\Longrightarrow$ Do not generate emissions in jet regime

(In original algorithm: vetoed shower - $Q_{ab} < Q_{\rm cut}$ is not present)

- But: evolution parameter t may be different from jet parameter $Q \Longrightarrow$ Truncated showering

Introduced in P.Nason, JHEP 0411 (2004) 040



- NB: In original algorithm, these emissions have been dealt with by radiating off the outgoing legs - in principle: logarithmically correct, in practice: may lead to unphysical colour flows

(Especially for angular-ordered showers, less severe if $t \simeq Q$)

The ME regime: Sudakov reweighting

- Look into ME-splitting kernel:

$$\mathcal{K}_{ab}^{\rm ME}(\xi,\bar{t}) = \mathcal{K}_{ab}(\xi,\bar{t})\Theta\left[Q_{ab}(\xi,\bar{t}) - Q_{\rm cut}\right].$$

$\Longrightarrow$ Generate emissions in jet regime only

($Q_{ab} < Q_{\rm cut}$ is not present)

- But these emissions are dealt with by higher order ME's
  $\Longrightarrow$ Reject complete event.

(Simple to see: This is the Sudakov rejection of original method)

The algorithm in a nutshell

- Select parton level event (ME: flavours, colours, momenta) according to corresponding (partial) cross section
- Cluster backwards with "inverted" shower (kinematics): yields $\{t, \xi, \phi\}$ of "hard nodes" (branching kinematics)

(Implementation of non-QCD splitting functions helps)

- Reweight with ratios $\alpha_s(\mu_{\rm node})/\alpha_s(\mu_{\rm ME})$ (QCD emissions)
- Start shower at highest scale, run truncated showers until scale of next hardest emission node. Reject event if new jet was produced
- Insert next node and repeat
- Obviously: If $Q = t$, then truncated shower not necessary

This is essentially L.Lonnblad, JHEP 0205 (2002) 046 for FS dipole showers.

Note: This procedure is independent of both shower and jet measure

ME & PS: Theoretical uncertainties

Uncertainties related to ME-PS merging

- Choice of parton shower implementation
- Choice of the jet criterion k_T-measure, soft eikonal, ...
- Value of the phase-space separation cut, $Q_{\rm cut}$
- Maximum number of jets from hard MEs, $N_{\rm max}$

Uncertainties related to pQCD methods

- Scale uncertainties from MEs
- Scale uncertainties from PSs
- PDF uncertainties

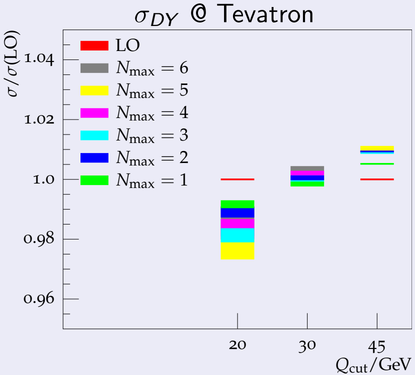
Two implementations currently available

- SHERPA - uses truncated CS-shower for initial and final state
- HERWIG++ - uses truncated angular ordered shower for final state

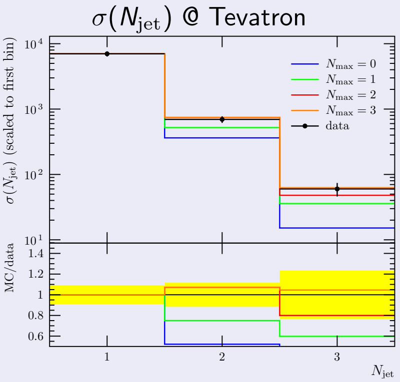
Results (DY @ Tevatron): Total cross sections

Consequence of the method:

- Cross section unaltered to LO accuracy
  (due to unitarity of PS simulation)
  $\longrightarrow$ can employ this to cross-check simulation
- Variation of Q_{cut} and/or N_{max} should not affect σ_{tot} too much



Results (DY Tevatron): Jet multiplicity



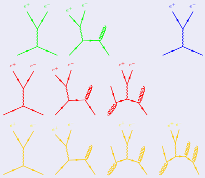
Data from Data: PRL100(2008)102001

Consequence of the method:

- Jet rates and -spectra improved compared to pure PS simulation

  (due to usage of HO real ME's)

- Note: minor corrections to total cross section might still have big effect on rare events !



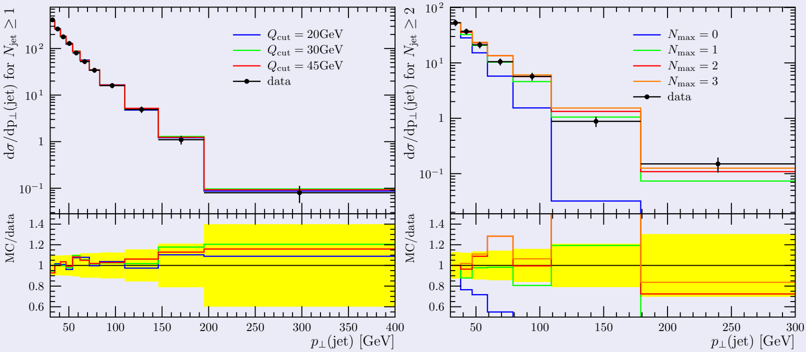
Results (DY Tevatron): Jet spectra

Data from Data: PRL100(2008)102001

Consequence of the method:

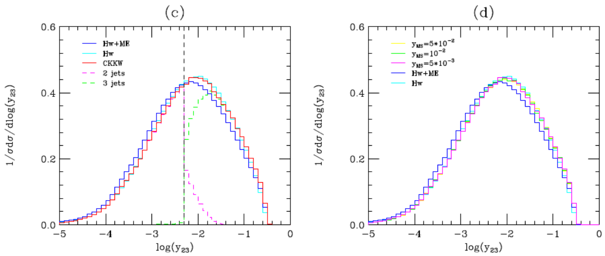
- Radiation pattern unaltered to PS accuracy
- Variation of Q_{cut} should not affect distributions too much

(But Q_{cut} must be in range where PS approximation is valid !)



ME & PS: The necessity of the truncated shower

(Use HERWIG++ as example: truncated showers not so visible in $p_\perp$-ordered showers)

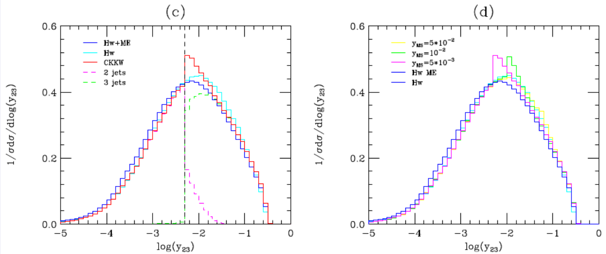


Truncated shower enabled

arXiv:0905.3072

Truncated shower disabled

arXiv:0905.3072



Forthcoming attractions in SHERPA, v.1.2.0

(All results above with SHERPA v.1.2.0)

- Including new ME generator COMIX:
  - Will allow for significantly higher multiplicities: $pp \to V + (\leq 6)j$, $Q\bar{Q} + (\leq 6)j$, $(\leq 6)j$ quite painless,

    (even more feasible - but painful due to integration)
  - No more libraries written out, compiled and linked.
- Including new Catani-Seymour shower

  (+ merging, of course);
- Automated Catani-Seymour subtraction

  (generic interface, massive dipoles work in progress).
- Automated decay chains for **all** heavy particles

  (up to now only user-defined decay chains feasible);

COMIX - a new matrix element generator for Sherpa

T.Gleisberg & S.Hoeche, JHEP **0812** (2008) 039

- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (cross sections):

$gg \longrightarrow ng$	Cross section [pb]				
n $\sqrt{s}$ [GeV]	8 1500	9 2000	10 2500	11 3500	12 5000
Comix	0.755(3)	0.305(2)	0.101(7)	0.057(5)	0.019(2)
Maltoni (2002)	0.70(4)	0.30(2)	0.097(6)		
Alpgen	0.719(19)				

σ [μb]	Number of jets						
$b\bar{b}$ + QCD jets	0	1	2	3	4	5	6
Comix	470.8(5)	8.83(2)	1.826(8)	0.459(2)	0.1500(8)	0.0544(6)	0.023(2)
ALPGEN	470.6(6)	8.83(1)	1.822(9)	0.459(2)	0.150(2)	0.053(1)	0.0215(8)
AMEGIC++	470.3(4)	8.84(2)	1.817(6)				

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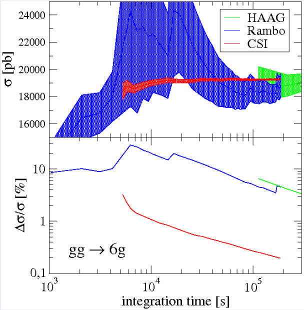
- Colour-dressed Berends-Giele amplitudes in the SM
- Fully recursive phase space generation
- Example results (phase space performance):



Using Catani-Seymour splitting kernels

First discussed in: Z.Nagy and D.E.Soper, JHEP **0510** (2005) 024;
Implemented by M.Dinsdale, M.Ternick, S.Weinzierl Phys.Rev.**D76** (2007) 094003,
and S.Schumann& F.K., JHEP **0803** (2008) 038.

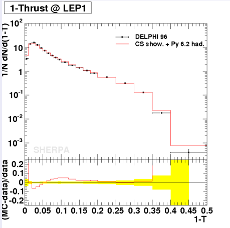
- Catani-Seymour dipole subtraction terms as universal framework for QCD NLO calculations.
- Factorisation formulae for real emission process:

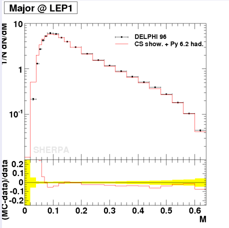
  Full phase space coverage & good approx. to ME.
- Added benefit: All particles always on-shell

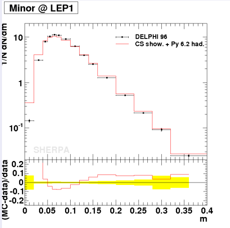
Matching/merging with ME improved.

Results in e^+e^- collisions at LEP1

S.Schumann& F.K., JHEP **0803** (2008) 038.







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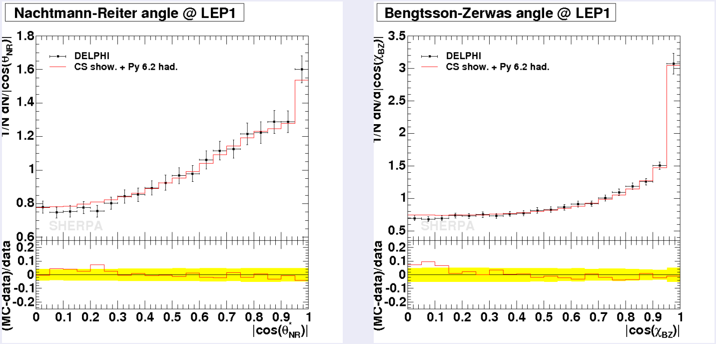
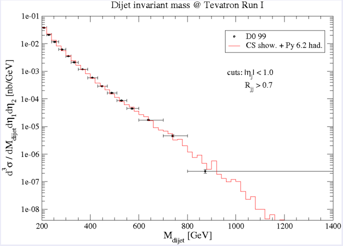
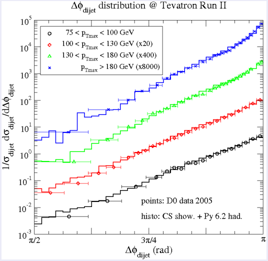


CS-Shower: Results in $p\bar{p}$ collisions

S.Schumann& F.K., JHEP **0803** (2008) 038.





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